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Stochastic acceleration of electrons at collisionless quasi-perpendicular shocks: PIC simulation

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Non-thermal electrons with power-law energy spectra are directly observed at Earth's quasi-perpendicular bow shock. Such high-energy electrons are thought to be accelerated through scatterings by electromagnetic waves upstream and downstream of the shock. In fact, Oka et al. (2017, 2019)[1, 2] reported in-situ evidences of pitch-angle scattering of non-thermal electrons by whistler waves at Earth's bow shock, using data provided by the Magnetospheric Multiscale (MMS) mission. However, the precise process of electron acceleration remains unclear.

Here we show a formation of electron power-law spectrum at quasi-perpendicular shocks in one-dimensional but long-term (>2000 electron-cyclotron periods) particle-in-cell (PIC) simulations. The shock parameters are as follows. The Alfvénic Mach number is 7.1, upstream plasma beta is 0.3, and the shock angle is 70 degrees. The ion-to-electron mass ratio is 625 and the ratio of electron plasma to cyclotron frequency is 10.

Figure 1(a) shows the numerically obtained electron energy spectra at far upstream and foot regions by dashed and solid lines, respectively. Here the electron energy is evaluated at the shock rest frame of reference, and is normalized by the incoming ion bulk energy. While the energy distribution far upstream represents the thermal incoming electrons, the distribution at foot region of the shock looks like a power-law shape, representing that the non-thermal electrons are produced near the shock transition region.

Figure 1(b) shows the example of accelerated electron's trajectories by colored lines. The background image with gray scale shows the magnetic field power. The simulation is in the downstream frame of reference, and the shock travels in the negative x-direction toward the upstream region. Foot and overshoots in the shock transition region exist as the quasi-perpendicular shock structure. Also, the intense field power in the magnetic overshoot is oscillating with about the quarter of the ion-cyclotron period, $\pi/2$. This is the evidence of the cyclic reformation of the shock. The electron (shown by the blue line) is reflected the increased magnetic field in the overshoot, and finally transmitted to downstream region with energy gain. Another electron (shown by the red line) is trapped between the first and second overshoots downstream, resulting in the energy gain, and finally transmitted to upstream region. Our PIC simulation has reproduced the features of the MMS observation such as the electron burst at the shock transition region and the electron hole in the pitch-angle distribution downstream [1]. We will demonstrate (1) properties of upstream and downstream whistler waves, (2) evolutions of electron's pitch-angle and energy distributions, and (3) processes of electron injection and acceleration.

References
[1] Oka, M., et al., Electron scattering by high-frequency whistler waves at Earth's bow shock, Astrophys. J., 842:L11 (2017)
[2] Oka, M., Otsuka, F., Matsukiyo, S., et al., Electron scattering by low-frequency whistlr waves at Earth's bow shock, Astrophys. J., 886:53 (2019)

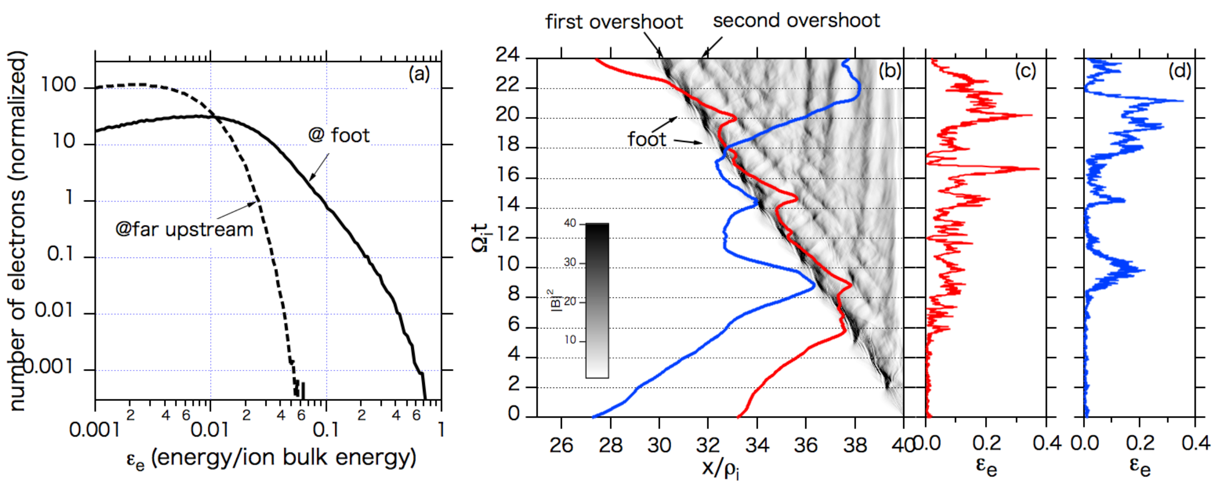

Figure 1: (a) Electron energy distributions at $t\Omega i$=21.2 for foot and far upstream regions. (b) Accelerated electron trajectories in (x-t) space and (c, d) corresponding energy evolutions. In (b) the image indicates magnetic field power.